Environmental Implications of the Spill from Water Reservoir No. 2 at Key Lake

March 1984

ENVIRONMENTAL IMPLICATIONS OF THE SPILL FROM WATER RESERVOIR NO. 2 AT KEY LAKE

March 1984

TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1.1
2.0	ENVIRONMENTAL BACKGROUND	2.1
3.0	ANTICIPATED BEHAVIOUR OF MATERIALS RELEASED FROM RESERVOIR NO. 2 INTO THE NATURAL ENVIRONMENT	3.1
	3.1 Water Quantity and Temperature	3.2
	3.2 Suspended Solids	3.2
	3.3 Total Suspended Solids	3.3
	3.4 Adsorption of Trace Materials onto Suspended Solids	3.3
	3.5 Summary	3.4
4.0	ANALYSIS OF DATA COLLECTED DURING AND AFTER THE SPILL	4.1
	4.1 Trace Elements	4.2
	4.2 Radionuclides	4.3
	4.3 General Water Quality Parameters	4.4
	4.4 Ammonia	4.5
	4.5 Summary	4.5
5.0	ENVIRONMENTAL SIGNIFICANCE	5.1
	5.1 Physical Impacts	5.1
	5.2 Chemical Impacts	5.2
	5.3 Radiological Impacts	5.3
	5.4 Effect of Unrestricted Discharge from Gerald Lake on Downstream Water Quality	5.4
6.0	CONCLUSIONS	6.1
7.0	RECOMMENDATIONS	7.1

1.0 INTRODUCTION

On 5 January 1984, a spill of 87,300 m^3 of water occurred because of the overtopping of a retaining dyke at water storage Reservoir No. 2 at the Key lake mining facility. This spill washed across a road and down into the northeast corner of Gerald Lake. Upon reaching the lake, the spill water broke through the ice and entered the lake itself. At about the same time, water was noticed flowing out of the far end of Gerald Lake into a muskeg drainage ditch and down toward a set of culverts that channel water flow to Wolf Lake and eventually to David Creek. In the absence of analytical data, a decision was made to stop the flow at the culverts and a temporary dyke was constructed to hold back any "spill waters". Steps were also taken to pump the water ponded against the dyke back into the mill to be used as process water. During all of this activity, water and sediment samples were being collected from Gerald Lake and the muskeg drainage ditch to the northwest through which water was observed to be flowing during and immediately after the spill.

Immediately following the spill, there was a great deal of uncertainty expressed in the media as to the environmental and possible public health consequences associated with the spill. The purpose of this report is to review the analytical data collected during and after the spill and to relate it to the natural environment of the Gerald Lake basin. The study addresses, in an objective way, the spatial extent of the spill and the ecological and public health consequences of the spill. In particular, the report addresses the consequences of the spill to the Gerald Lake ecosystem, the fate of the various abundant chemicals such as calcium, ammonia and sulphate, trace elements such as nickel, uranium, zinc and arsenic and a radionuclide, radium-226, and the possible consequences to the downstream ecosystem if no remedial action were to be carried out. Based upon the findings, a set of conclusions and recommendations are made.

2.0 ENVIRONMENTAL BACKGROUND

Gerald Lake, a small lake measuring about 400 m by 250 m and having a mean depth of about 5 m, is located in the Yak Creek sub-basin of the David Creek Watershed which flows into the Wheeler River. The Yak Creek sub-basin covers 7.4 km^2 and includes Gerald Lake, Fox Lake, Raven Lake and Wolf Lake (Figure 1). Data collected in 1978 showed peak flows from this watershed of 210 L/sec in September, and from December to April the creek freezes so that discharge is minimal. The average flow from this system was 100 L/sec during the open water period from the end of April until the beginning of December. Average annual flows based upon aerial yield are expected to be on the order of 50 L/sec. The catchment area of Gerald Lake itself is estimated to be on the order of 20 ha. A bathymetric map of Gerald Lake is shown in Figure 2.

Gerald Lake is surrounded on the north and eastern sides by a high ridge of glacial till. This till is well drained and supports a stoney sandy loam soil. Jack pine and black spruce are the dominant forest types on this soil. On the northern and western shore of Gerald Lake are muskeg deposits overlying the glacial till. This muskeg is very poorly drained and supports a sphagno fibrosol type of soil. This type of soil has been found, in many places, to have a very high capacity for trace element adsorption and complexation.

The natural drainage from Gerald Lake was originally through a series of poorly defined channels in the muskeg to Wolf Lake. With development of the site, the drainage from Gerald to Wolf Lake was channelized. The road to the waste management area passed over drainage channels in the muskeg, and culverts were placed under the road to facilitate drainage.

Gerald Lake itself is one of a large number of small boggy headwater lakes in northern Saskatchewan. Baseline environmental studies for the area have shown the presence of burbot as the only fish species, but it is likely that other species such as sticklebacks and other small cyprinid species may also be present. The soft organic sediments in the lake are expected to support a relatively productive midge population which, along with other invertebrate and plankton species, form the food base for the fish in the lake. No sport fishery exists in Gerald Lake nor the lakes immediately downstream in the Yak Creek watershed.

FIGURE 1

Yak Creek Watershed

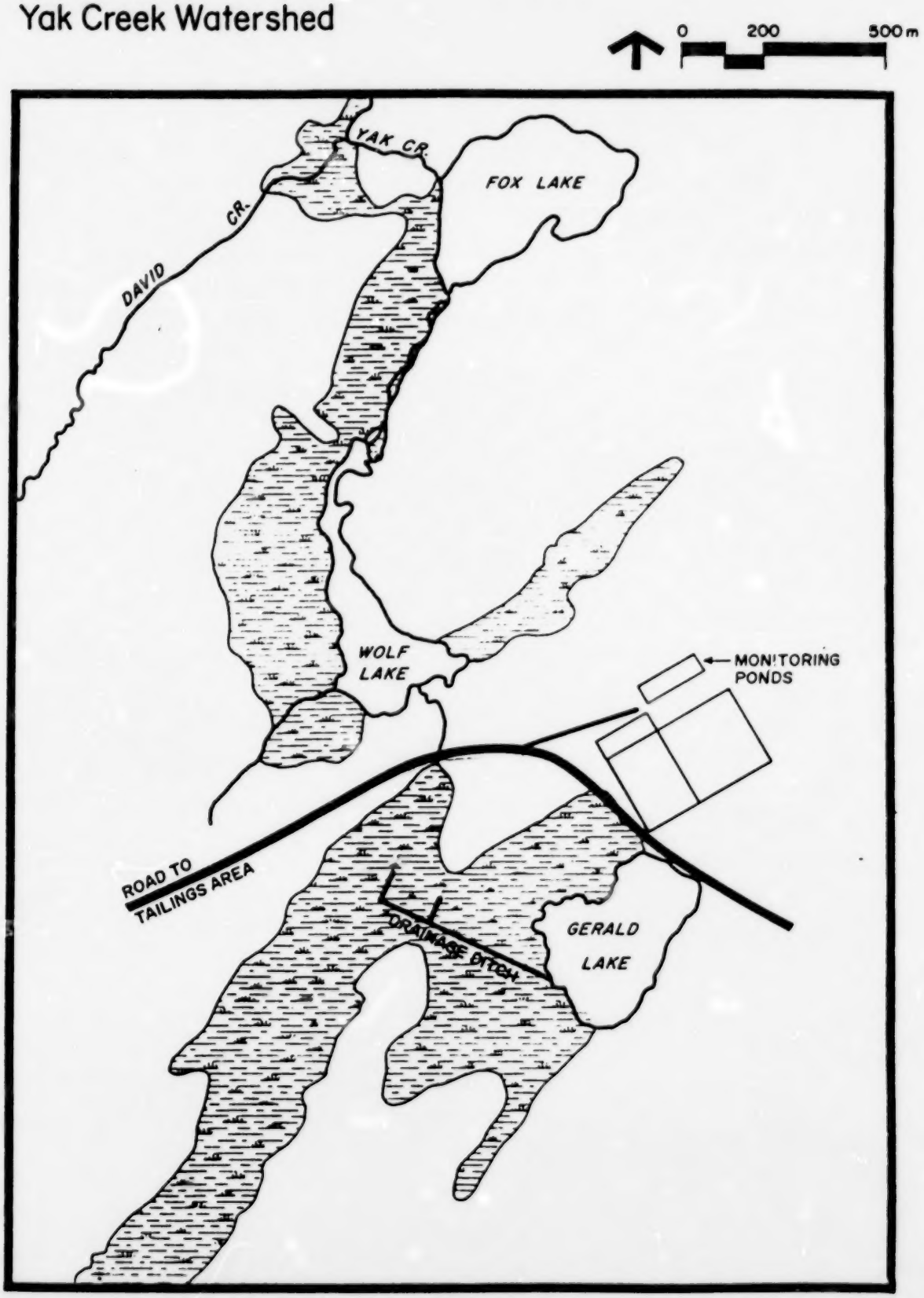
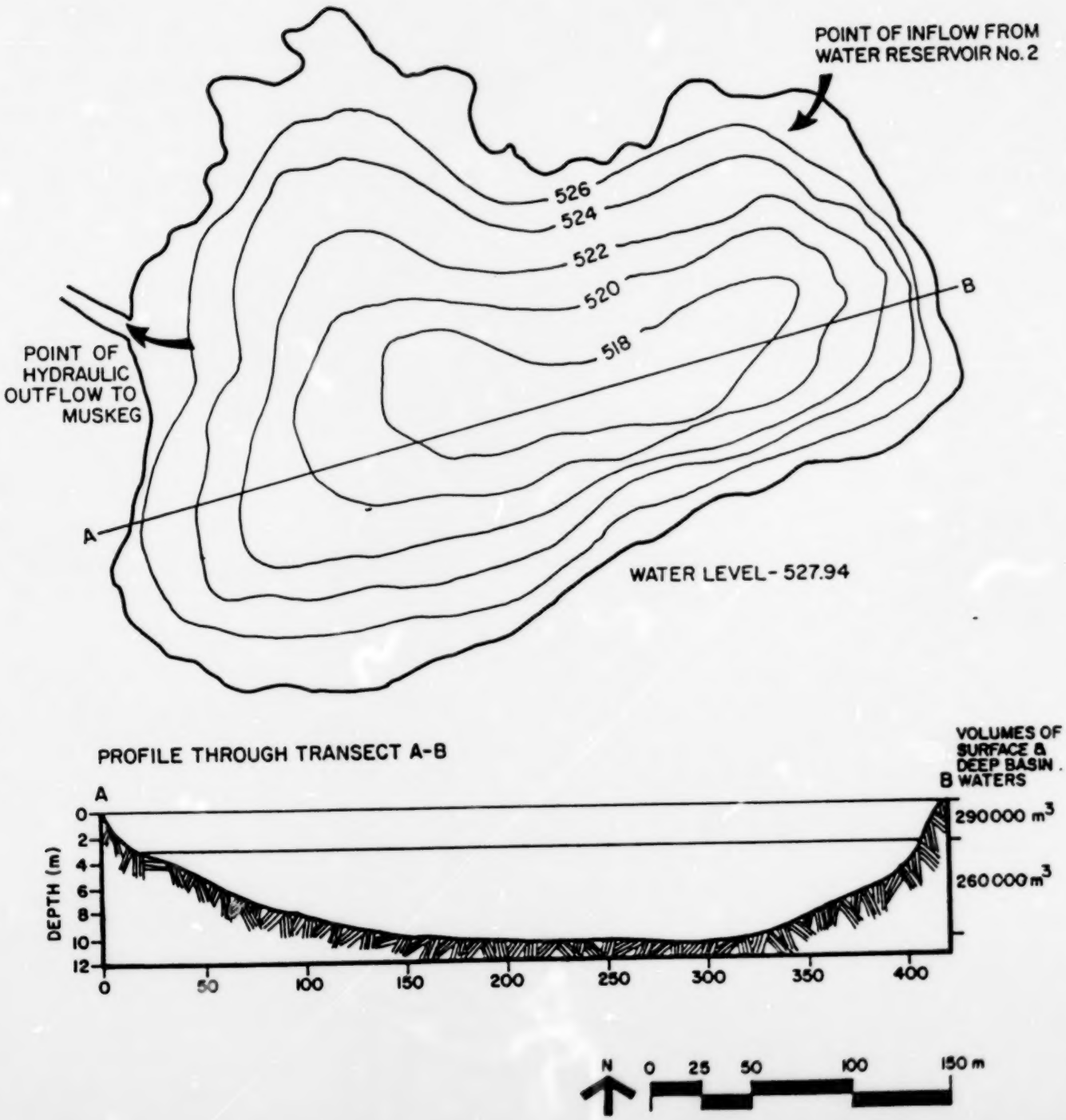


FIGURE 2
Bathymetry of Gerald Lake



The area of muskeg to the north and west of Gerald Lake is a relatively unproductive habitat, being used only occasionally by large mammals which may venture near the mine site. The lack of suitable habitat and food supply precludes the use of the area by aquatic furbears such as muskrat, otter or beaver.

The sediments of Gerald Lake in the deep basin are expected to be very organic rich and have a relatively high capacity for trace element and radionuclide adsorption.

Background water quality for Gerald Lake and its outflow through the muskeg area is presented in Table 1.

In summary, Gerald Lake and its catchment area is very typical of a large number of small headwater lakes in northern Saskatchewan. Its volume of 550,000 m^3 when combined with a small catchment area of 20 ha results in a long hydraulic residence time on the order of 18 years. This means that the rate at which soluble materials will be washed through it will be very slow.

TABLE 1: BACKGROUND WATER QUALITY RANGES FOR GERALD LAKE AND MUSKEG AREA TO THE NORTHWEST

Parameter	Location	
	Gerald Lake	Muskeg Channel
pH	6.2-6.9	4.2-5.0
Conductivity (us/cm^2)	15-19	28-53
Calcium (mg/L)	0.7-1.0	0.6-1.4
Magnesium (mg/L)	0.2-0.4	0.05-0.6
Potassium (mg/L)	0.7-1.2	0.5-1.0
Sodium (mg/L)	1.2-4.5	1-4.2
Sulphate (mg/L)	1.0	1.0
Bicarbonate (mg/L)	5.0-8.1	0.0-6.0
Chloride (mg/L)	1-2	1-1.4
Kjeldahl N (mg/L)	0.29-0.76	1.9-45.0
Ammonia N (mg/L)	0.02	0.12
Copper (ug/L)	1-8	2-4
Lead (ug/L)	3-4	2-4
Zinc (ug/L)	5-18	8-18
Arsenic (ug/L)	0.5	0.5
Nickel (ug/L)	1-5	1-5
Uranium (ug/L)	0.5	0.5
Radium-226 (Bq/L)	0.004-0.01	0.07-0.41
Lead-210 (Bq/L)	0.004-0.01	0.01-0.12

3.0 ANTICIPATED BEHAVIOUR OF MATERIALS RELEASED FROM RESERVOIR NO. 2 INTO THE NATURAL ENVIRONMENT

When the dyke containing the water in storage Reservoir No. 2 was breached and water began flowing down into Gerald Lake, the water released and the materials it contained had physical and chemical properties which would dictate to a large degree their movement in the natural environment. The water released may be thought of in terms of:

- the water itself, its volume and its temperature and temperature-related density;
- the suspended solids arising both from those solids suspended in the reservoir and those suspended solids picked up from eroding dyke material; and
- the dissolved solids or materials which are in solution (often defined as those materials passing through a 0.45 micron filter).

It must be recongized that there is an ongoing and dynamic exchange of many materials between soluble and particulate phases. This distribution or partitioning coefficient, which describes this exchange, is influenced by a variety of environmental variables such as redox potential (level of free oxygen present), concentration of total dissolved solids, and pH. Perhaps the most important of these is pH. At higher pH values, hydroxides of many metals form and the level of metals in 'solution' drops very low.

The materials released from Storage Reservoir No. 2 may be, for discussion purposes, be expected to be influenced in their distribution in Gerald Lake by the following properties:

1. water quality and temperature,
2. level of suspended solids,
3. level of dissolved solids, and
4. adsorption and sedimentation of trace elements and radionuclides.

A short discussion of the properties of the water released from Reservoir No. 2 and how these properties affect its behaviour and the behaviour of the materials contained in it follows.

3.1 Water Quantity and Temperature

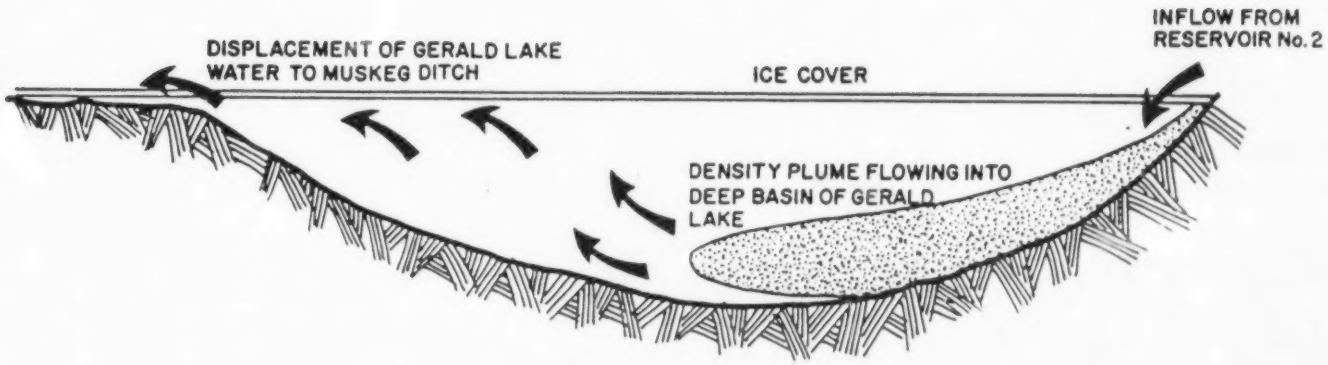
The best available estimates suggest that approximately 87,300 m^3 of water was released from Reservoir No. 2 to Gerald Lake during the course of the spill in early January. Although no temperature data are available, it appears likely because of the recycled nature of this water and the fact that it melted and broke through the corner of Gerald Lake that its temperature was a few degrees above zero, possibly as high as 3-4°C. Water has its maximum density at 4°C. No temperature data are available for Gerald Lake before the spill but, based upon the lake's size, volume and depth, it would be reasonable to assume that the water immediately under the ice was at 0°C and that a slight thermal gradient existed in the deepest parts of the lake where the water temperature may have been as high as 1-1.5°C. If there were any groundwater inputs in parts of the lake, a small local thermal gradient close to the bottom may have existed. The total volume of Gerald Lake prior to the spill was estimated at 550,000 m^3, or about six times the volume of the spill. The surface area of Gerald Lake is approximately 10 ha and the volume of water occupying the first metre under ice cover is on the order of 100,000 m^3, or roughly equivalent to the volume of the spill. Based upon the expected density difference that was believed to exist between the water underlying the ice in Gerald Lake and the water from Reservoir No. 2 (a .013% thermal density difference), it is suspected that, because of the thermal density effect, the inflowing water would sink to the bottom of the lake displacing surface water out through the muskeg as the level of Gerald Lake rose the theoretical 0.87 metres in height. This is shown schematically in Figure 3.

3.2 Suspended Solids

The level of suspended solids in Reservoir No. 2 prior to the spill are estimated at close to 300 mg/L based on a sample collected of the overflow water on 5 January, the first day of the spill. This figure would be expected to have fluctuated considerably over the course of the spill as particulate material eroded from the dyke walls, and by 6 January the suspended solids level was down to 7 mg/L. Based upon an estimated 1,000 m^3 of dyke material being washed out in 87,300 m^3 of water, and assuming a bulk density of 2 (vs. a reported 1.94) for the washed out dyke solids, the average suspended solids level in the water entering Gerald Lake from the washed-out dyke is estimated to be near 20 g/L. The very fine materials may be expected to be about half of the total and these

FIGURE 3

Schematic of Density Plume Flow into Gerald Lake


DISPLACEMENT OF GERALD LAKE WATER TO MUSKEG DITCH
ICE COVER
INFLOW FROM RESERVOIR No. 2
DENSITY PLUME FLOWING INTO DEEP BASIN OF GERALD LAKE

fines would move out into the lake. This high fine suspended solids load may be expected to create on its own heavy turbidity plume which, having a density of close to 1% greater than Gerald Lake water, would be expected to sink into the deep basin of the lake. Much of the silts and clays washed out by the dyke would be expected to have a realtively strong adsorption capacity for trace elements and radionuclides and are suspected of 'scavenging' a high proportion of these elements and depositing them adsorbed to silts and clays as a fine layer over the deep basin of Gerald Lake. The area of suspected deposition is shown in Figure 4. This fine layer, on the order of a centimetre or so deep, except perhaps where the coarse materials deposited at the spill entrance to Gerald Lake, will soon be mixed by invertebrate activity with the underlying sediments. This activity may dilute the elements input to the lake to the point where after several years they may become indistinguishable from background. Initially, however, an area of relatively high sediment concentration should be evident in the deep basin of Gerald Lake underlying the plume of water that entered from Reservoir No. 2. Based upon basin morphology, it is anticipated that the thickness of sedimenting fines would be deepest near sediment sampling Station No. 6. Consequently, this is where the least dilution of dyke material with natural lake sediments is expected. This sample was accordingly assumed to be the most representative of sedimenting dyke fines.

3.3 Total Dissolved Solids

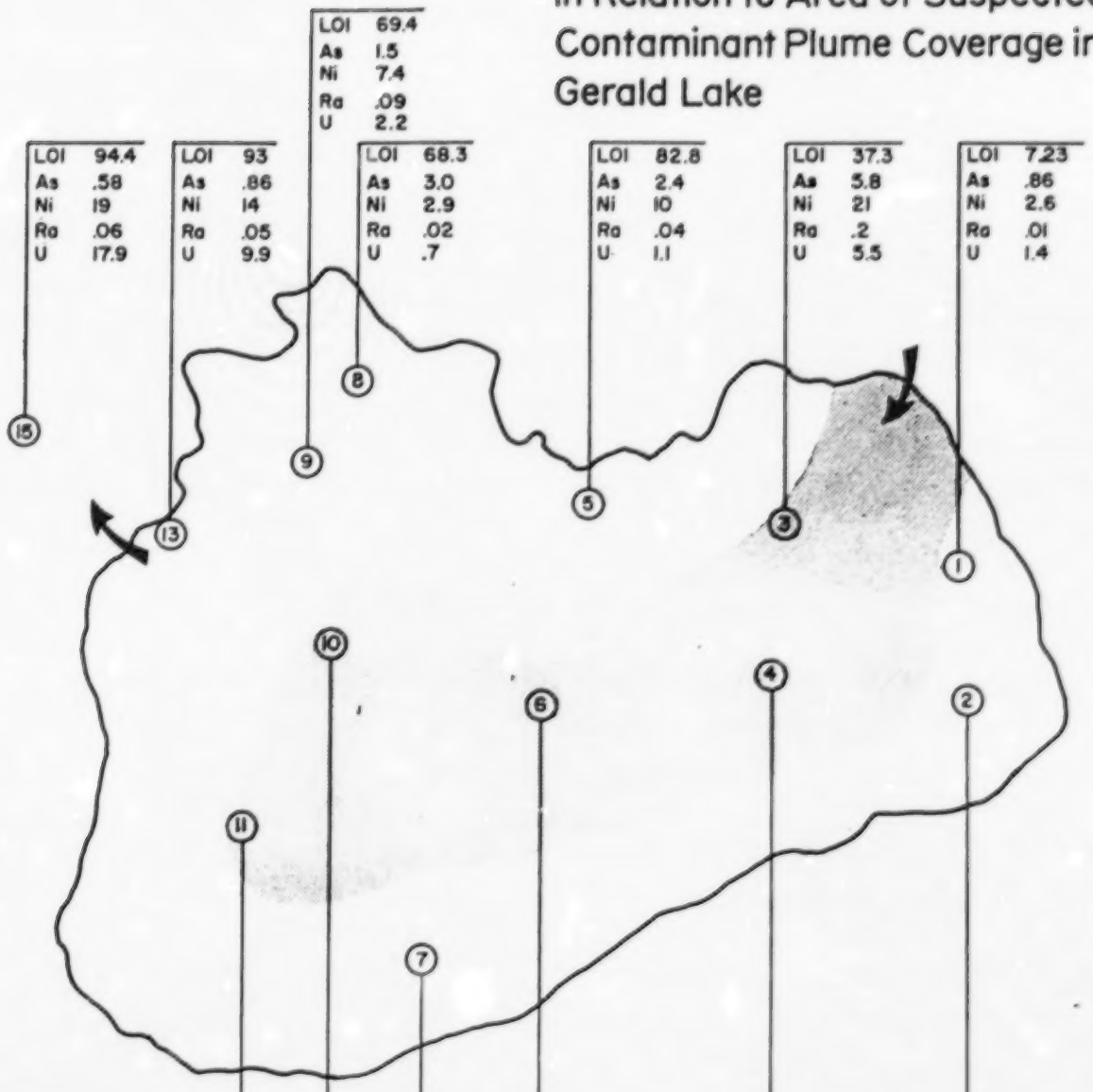
An analysis of total dissolved solids was not carried out on the samples collected, but this can be estimated based upon conductivity values and concentrations of the relatively soluble major anions and cations. A review of water quality data collected before, during and after the spill from Reservoir No. 2 suggest a conductivity on the order of 1,000 us/cm and that calcium and sulphate are the major dissolved materials. The total dissolved solids level would be expected to be near 1,000 mg/L. This would make the Reservoir No. 2 water about 0.1% heavier due to its total dissolved solids content than the water in Gerald Lake, and cause the inflow from Reservoir No. 2 to sink when it flowed into Gerald Lake.

3.4 Adsorption of Trace Materials onto Suspended Solids

When trace elements in solution in a waterbody come into contact with suspended particulates, there is a tendency to adsorb to the solid phase. This adsorption tendency is

FIGURE 4

Sediment Parameter Distribution in Relation to Area of Suspected Contaminant Plume Coverage in Gerald Lake



BACKGROUND IN GERALD LAKE

Ni 4 µg/g
U .5 µg/g

REGIONAL BACKGROUND

As 2–40 µg/g
Ni 14–230 µg/g
Ra 0.07–1.65 Bq/g
U 5–500 µg/g

LOI LOSS ON IGNITION (%)

LOI .5
As .6
Ni 2.2
Ra .01
U .7

LOI 13.5
As 5.0
Ni 24
Ra .25
U 7.4

LOI .97
As .56
Ni .8
Ra .06
U .6

LOI 52.6
As 2.4
Ni 4.6
Ra .04
U 1.0

LOI 21
As 16
Ni 87
Ra .8
U 25.6

REFERENCE SAMPLING LOCATION

LOI 45.9
As 2.8
Ni 7.6
Ra .09
U 1.7

Area of Lake Bottom Covered by Initial Spill Input and Sedimenting Dyke Fines

(7) Sampling Station Locations

often expressed as a distribution coefficient or a ratio of the quantity adsorbed onto particulate surfaces to that remaining in solution. The distribution coefficients for the radionuclides released from Reservoir No. 2 in the open water of shield lakes show a wide range of values but are often on the order of 1,000 to 10,000 mL/g. This simply means that, if water contains 1 g/L of suspended solids with a distribution coefficient of 1,000 mL/g, the dissolved material will partition itself evenly between the water and the suspended particulate material. If the coefficient is 10,000 mL/g, the distribution would be 90% on the solid phase and 10% in the water at the 1 g/L suspended solids level.

Thus, during and immediately after the spill, it would be expected that a very high percentage of the trace elements and radionuclides that were in solution in Reservoir No. 2 would react with the geochemically fresh silts and clays washed out of the dyke, and that most of these materials would settle to the sediments of Gerald Lake as a fine film on the bottom of the deep basin of the lake. The deep basin of Gerald Lake has an area of approximately 5 ha. If 1,000 m^3 of material were assumed to wash out of the dyke, about half of this material would be silts and clays which would be expected to deposit over the deep basin of Gerald Lake. These small particles would form a sediment layer about one centimetre thick. It is likely, however, these deposits are much thicker and coarser near the inflow to Gerald Lake and much thinner and finer near the far end. If we were to assume an average kd of 5,000 mL/g for the fine fraction, we would expect about twenty percent of the trace elements and radionuclides to remain in solution and about eighty percent of the material to be precipitated to the sediments, along with the dyke fill materials. Less reactive materials such as sulphate and ammonia would be expected to maintain a higher percentage in solution. Calcium, because of its high natural abundance, would not be expected to adsorb as high a percentage as the elements present in trace quantities. As discussed previously, chemical data from sediment sampling Station No. 6 is assumed to be representative of the fine sedimenting material washed into Gerald Lake.

3.5 Summary

Based upon considerations relating to water temperature, dissolved solids and suspended solids, the water entering Gerald Lake from Reservoir No. 2 would be expected to be considerably denser than the waters of Gerald Lake. The spill water would be expected to flow into the deep basin of Gerald Lake and displace the lake water upward causing

the lake water to spill over into the muskeg drainage ditches to where it would pond against the utilidor road. This is illustrated schematically in Figure 3. The contaminant plume would then be expected to oscillate in the lake basin and slowly mix with the overlying water. Complete mixing of the spill plume waters with the surface waters of Gerald Lake would not be expected until spring turnover, which will occur shortly after ice-out.

4.0 ANALYSIS OF DATA COLLECTED DURING AND AFTER THE SPILL

At or about midnight on 4 January 1984, a supervisor noted that water Storage Reservoir No. 2 had begun to overtop, and immediate action was initiated to stop all water flow into the reservoirs. Efforts during the night and early morning to stop the overflow leading toward Gerald Lake were unsuccessful. Early on Thursday afternoon, 5 January, the liner in Reservoir No. 2 was cut to prevent further undercutting of dam. After a significant quantity of water had entered Gerald Lake, water flow was noticed out of the northwest corner of Gerald Lake into a channel in the muskeg from where it drained northwest and was contained by the road leading to the waste management area. The flow from the reservoir to the Gerald Lake basin continued to diminish. On Friday, 6 January, the flow from Reservoir No. 2 had slowed to a trickle and by early Saturday morning, flows had stopped completely.

While water was draining through the break in water storage Reservoir No. 2, samples were taken to characterize the chemical nature of the water being lost, and reinforcing berms were being placed along the utilidor road leading to the waste management area to ensure all lost water was contained in the Gerald Lake basin and the muskeg channel leading to the utilidor road. These contaminant efforts were successful and consequently this evaluation will be centered on the Gerald Lake basin and the muskeg drainage ditch above the utilidor road. An estimated 87,300 m^3 of water from the water storage reservoirs was estimated to have entered the Gerald Lake basin. The area affected by the loss of water from Reservoir No. 2 is shown in Figure 5. There was no evidence of any water passing the utilidor road culverts.

The quality of this water, as estimated based upon a sample collected of water flowing out of Reservoir No. 2 at 5:30 p.m. on 5 January 1984 and a sample collected at 5:00 p.m. on 6 January 1984 for Ra-226 analysis, is as appears in Table 2. Table 2 also presents background water quality data for Gerald Lake, and the muskeg drainage ditch to the northwest; predicted post-spill concentrations and actual monitored post-spill concentrations in the deep basin of Gerald Lake at a depth of below 3 m, in the surface waters of Gerald Lake and the muskeg drainage channel to the northwest.

Based upon the density of the water entering Gerald Lake from Reservoir No. 2, all of the theory predicts that the contaminant plume would sink into the deep basin of the

FIGURE 5
Spatial Extent of Spill from Reservoir No.2

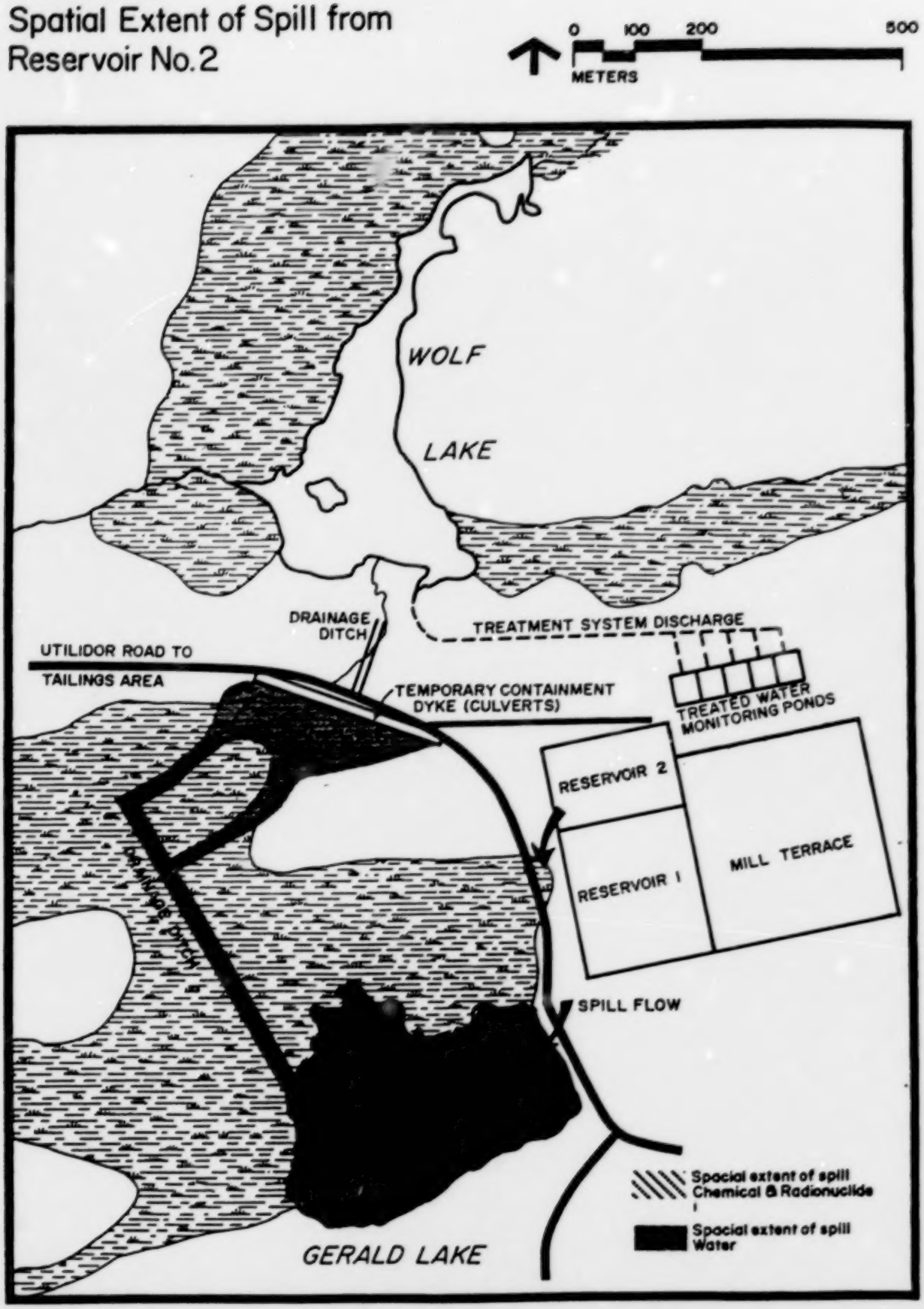


TABLE 2: GERALD LAKE LOADINGS AND MONITORING CORRELATION

Parameter	Baseline Conc. Range in Gerald Lake	Estimated Concentration in Reservoir No. 2 Spill	Predicted Post-Spill Conc. Fully Mixed in Deep Basin	Predicted Post-Spill Conc. Deep Basin, 15 Jan. Monitoring Stns. 4, 6 & 10	Post-Spill Conc. in Surface Waters of Gerald Lake 10% of Deep Basin Values	Post Spill Conc. in Surface Waters of Gerald Lake 10 & 17 Jan.	Post-Spill Conc. in Muskeg Channel to N.W. of Gerald Lake 5% of Deep Basin Value	Post-Spill Conc. in Muskeg Channel to N.W. of Gerald Lake 11, 18, 22 January 1984	Baseline Conc. in Muskeg Channel to N.W. of Gerald Lake
pH	6.2-6.9	9.2		8.5-9.1	6.5-7.0	6.6	5.0-6.0	5.6-7.0	4.2-5.0
Conductivity (us/cm)	15-19	1,000	350	325-447	35	35-60+	35	4-18	28-53
Cu (ug/L)	1-8	10	4	no data	5	6	5	1	2-4
Pb (ug/L)	3-4	20	10	2-5*	5	2-6	5	1-5	2-4
Zn (ug/L)	5-18	80	25	4-9*	20	3	20	1-2	8-18
Ni (ug/L)	1-5	1,200	400	20-70*	40	3-20	20	1-18	1-5
As (ug/L)	0.5	150	50	0.5-19*	5	0.5-1.9	3	0.5-0.6	0.5
U (ug/L)	0.5	600	200	54-98*	20	1-14	10	0.5-5	0.5
Ra-226 (Bq/L)	0.004-0.01	10	3	0.30-0.57*	0.3	0.02-0.09	0.2	.001-0.09	0.07-0.41
SO_4 (mg/L)	1	500	150	108-182	15	3-14+	10	1.3-14.0	1
Cl (mg/L)	1-2	15	7		2	0.3	2	0.15	1-1.4
NH_4 (mg/L)	0.01-0.02	14	5	3-10	1	0.1-0.8	1	0.3-0.7	0.1
TKN (mg/L)	0.29-0.76	35	10	4.7-5.9*	1	0.4-1.2	50	0.7-1.3	2-45
Ca (mg/L)	0.7-1.0	200	65	53-74	5	3-6+	3	0.23-6.3	0.6-1.4
Mg (mg/L)	0.2-0.4	10	4		1	0.5	1	0.6	0.05-0.6
Na (mg/L)	0.6-4.5	15	5		5	1.7	5	1.8	1-4.2
K (mg/L)	0.7-1.2	5	2		2	0.3	1	0.4	0.5-1.0

*Monitored values lower than predicted.

+17 January Station 11 Gerald Lake outlier not included.

Assumed dilution ratio = 3:1 in deep basin waters.

lake, and all of the data collected after the spill would appear to confirm this prediction. Temperature and conductivity profiles collected in mid-February from Gerald Lake (Figure 6) show that a month and one-half after the spill, conductivity (dissolved solids) and temperature stratification are still present. Analytical data collected at the stations shown for conductivity and radium-226 in mid-January are shown for comparative purposes. These data show that in mid-January conductivity and radium-226 values were about ten times higher in the deep basin of Gerald Lake than in the surface waters. Conductivity and thermal data collected in mid-February show that the situation has not changed significantly since then, and that the water immediately under the ice which is flowing into the muskeg channel is at background concentrations with respect to most of the variables analyzed for.

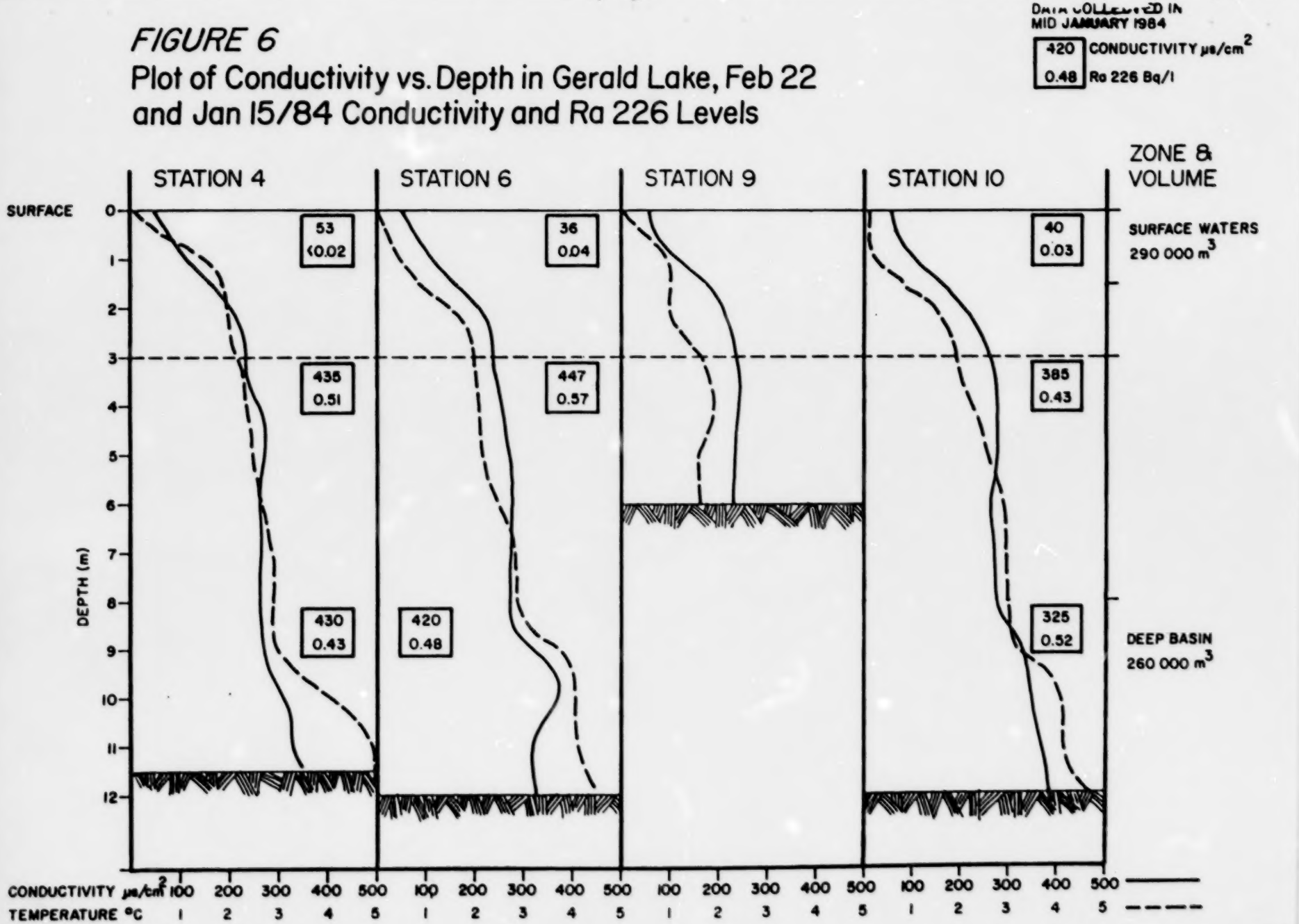
The following is a short discussion of how monitoring data collected before, during and after the spill tie together for the most important parameters viewed from both an environmental and public concern. The analysis addresses the fate of materials from a mass balance standpoint and based upon the data available attempts to achieve a convergence between the amount of material lost to the Gerald Lake basin during the spill and the amount of material accounted for in the water column and sediments.

4.1 Trace Elements

Trace elements are those elements generally present in the environment in microgram per litre quantities in water, or microgram per gram quantities in solid materials such as sediments. Some of these elements such as copper, nickel and zinc are essential trace nutrients, whereas others such as lead, arsenic and uranium have not been shown to be essential trace elements for man. All of these elements, if present in too high a quantity in the diet of man, or in the water in which fish and other aquatic species live, are undesireable in high concentrations and capable of causing toxic effects. The concentrations of these trace elements is very low in the Gerald Lake basin, and the uncertainties associated with the analytical data pertaining to them are expected to be relatively high. Uranium is considered in the trace contaminant group as it is present in the environment at similar levels to other trace elements and its chemical toxicity and radiotoxicity are approximately equal.

FIGURE 6

Plot of Conductivity vs. Depth in Gerald Lake, Feb 22 and Jan 15/84 Conductivity and Ra 226 Levels



The trace elements marked with an asterisk in Table 2 have monitored values less than that predicted as a result of straight dilution in the deep basin of Gerald Lake. The concentration of these trace elements monitored in the surface water of Gerald Lake and the muskeg drainage channel to the northwest is not significantly different from background and thus dilution in the surface waters of Gerald Lake cannot account for the discrepancies. Lead, zinc, uranium and arsenic are about two to five times lower than predicted. Adsorption onto particulates washed in from the eroding dyke was expected to account for a reduction of about five times the predicted water concentration in the deep basin of Gerald Lake. This is close to the observed values for lead, zinc and arsenic. The average nickel concentration was observed to be 0.04 mg/L in the deep waters of Gerald Lake, or one-tenth the predicted concentration. The levels of trace elements and radium-226 found in the sediments of Gerald Lake in mid-January are shown in Figure 4. Regional background ranges are also shown for reference. The levels found at Station 6 in the middle of the area where the turbidity plume was expected to have settled were used for the mass balance calculations shown in Table 3. These mass balance calculations show good convergence and tend to confirm that the trace elements not accounted for in the water analyses have deposited in the deep basin sediments of Gerald Lake.

4.2 Radionuclides

Radium-226 is the only radionuclide other than uranium for which adequate monitoring data are available in order to carry out mass balance calculations. The level of Ra-226 in the deep basin of the lake is as was the case for nickel, about ten times lower than that which dilution alone would account for. This would suggest, given the very low levels found in the surface waters and in the muskeg drainage channel, that about 90% of the radium that entered Gerald Lake was precipitated to the sediments. Sediment analyses in the deep basin of Gerald Lake at Station 6 produced a value of 0.8 Bq of Ra-226 per gram of sediment. If the average concentration within the deposited sediment plume is assumed to be 0.8 Bq/g, and if it is assumed that most of the radium in the sediment above background is adsorbed onto the estimated 500 m^3 of silts and clays that washed in from the Reservoir No. 2, then the total quantity of Ra-226 in these deep sediments would be 8×10^8 Bq. The quantity of radium in the water of the deep basin of Gerald Lake assuming a volume of 260,000 m^3 (Figure 6) and an average concentration of 0.5 Bq/L (Table 2) would be 1.3×10^8 Bq, for a total of 9.3×10^8 Bq of radium accounted for

TABLE 3: . MASS BALANCE CALCULATIONS ON MATERIALS LOST FROM WATER STORAGE RESERVOIR NO. 2

Parameter	Quantity Lost from Reservoir No. 2 in g (%)	Quantity in Sediment of Gerald Lake in g (%)*	Quantity in Deep Water of Gerald Lake in g (%)	Quantity in Surface Water of Gerald Lake in g (%)	Quantity in Muskeg Drainage Channel to Northwest of Gerald Lake in g (%)	Environmental Balance
Calcium	17.4×10^6 (100)	ND	16.25×10^6 (93)	1.9×10^6 (11)	$.087 \times 10^6$ (0.5)	+5%
Sulphate	43.5×10^6 (100)	ND	41.6×10^6 (95.6)	2.9×10^6 (6.7)	0.87×10^6 (2)	+4%
Nickel	104×10^3 (100)	87×10^3 (84)	10.4×10^3 (10)	3.1×10^3 (3)	0.4×10^3 (1)	-3%
Arsenic	13×10^3 (100)	16×10^3 (123)	3.4×10^3 (26)	0.2×10^3 (1.5)	ND	+50%
Uranium	52×10^3 (100)	25×10^3 (48)	24×10^3 (46)	2.3×10^3 (4)	0.17×10^3 (0.3)	-2%
Radium-226	23×10^{-3} (100)	22.4×10^{-3} (97)	3.5×10^{-3} (15)	0.23×10^{-3} (1)	0.02 (.1)	+13%
Ammonia	1.2×10^6 (100)	ND	1.3×10^6 (108)	$.14 \times 10^6$ (12)	0.05×10^6 (4)	+24%

*Sediment quantities derived from concentrations at Station 6.

Note: The fact that the environmental balance does not always add up to 100% is a reflection of sampling and analytical variability.

in Gerald Lake water and sediment. The quantity lost from Reservoir No. 2 assuming an average concentration of 10 Bq/L and a volume of 87,300 m^3 would be 8.7×10^8 Bq. Thus, based upon the limited analyses available, it appears that of the 23 mg (8.7×10^8 Bq) of radium believed lost from Reservoir No. 2, about 22 mg is in the sediments and 3.5 mg in the deep water. The concentration in the surface waters of Gerald Lake and in the muskeg drainage channel was not considered sufficiently different from background to contribute significantly to the mass balance.

4.3 General Water Quality Parameters

The materials that are not expected to react with sedimenting materials, such as calcium, sulphate and general parameters such as conductivity are all in the ranges predicted based simply on dilution (Table 2). Sulphate ion because of its abundance is a relatively good tracer of the water mass that left Reservoir No. 2. Its monitored distribution in the deep waters of Gerald Lake suggests that 95% of it could be accounted for there (Table 3). The surface waters have levels averaging near 10 mg/L. On a mass basis, about 87×10^6 L x 500 mg sulphate/L or 43.5×10^6 g of sulphate was lost in the spill from Reservoir No. 2. The deep water of the lake contains 260×10^6 L x 160 mg/L or 41.6×10^6 g, while the surface waters contain 290×10^6 L x 10 mg/L or 2.9×10^6 g of sulphate, for a total in the lake of $41.6 + 2.9 = 44.5 \times 10^6$ g. A further 87,000 m^3 of water was displaced out of Gerald Lake during the spill into the muskeg drainage channel and ponded against the utilidor road. Concentrations in this water ranged from 1-15 mg/L (Table 2) with an average value on the order of 10 mg/L. This would account for a further 0.87×10^6 g of sulphate for a total in the system of about 45.4×10^6 g. If the background level of sulphate from Gerald Lake is corrected for (reported at $<$ 1 mg/L), it amounts to about $.55 \times 10^6$ g. Thus, the discrepancy in accounting for all of the sulphate and by implication all of the trace materials that remained in solution lost through the spill is on the order of 3% which is extremely close considering the uncertainty in the volumes and analysis.

A similar calculation for calcium ion which is present in excess in the system and, therefore, may be expected to be relatively unreactive shows an excess of about 15% in the Gerald Lake basin over that which would be expected based upon expected loadings. It should be noted that there are much fewer calcium analyses than sulphate and the uncertainty in the data would be expected to be higher. For example, if one high calcium

value is left out of the lake calculation, a loading of 200 mg/L is assumed and a background correction is made, the excess calcium is only 5%. This high anomalous value was left out of the calculations in Table 3.

4.4 Ammonia

The major anion of concern from an environmental standpoint is ammonia. The average deep water concentration was observed to be 5 mg/L; in mid-January, the average surface concentration was .38 mg/L; and the average release from Reservoir No. 2 was 14 mg/L. The mass released from the reservoir was 1.2×10^6 g and the amount in the deep water is 1.3×10^6 g and in the surface water 0.14×10^6 g. The mass balance for ammonia, as presented in Table 3, is thus out by about +24% if the muskeg channel is considered, with the background correction being insignificant. The pH of the deep water in Gerald Lake monitored in mid-January was close to 9 and, at this pH, the ammonia dissociates to about 10%, resulting in a concentration of unionized ammonia N of about 0.5 mg/L or about .65 mg/L of unionized ammonia. Both the quantity of total ammonia and the quantity of unionized ammonia is important from a toxicity standpoint.

4.5 Summary

In spite of the limited analyses that have been carried out during the actual spill, there is very good convergence with the loading data. All of the reactive trace elements show a deficiency in water column concentration of the order to be expected if adsorption and sedimentation were the removal processes. This hypothesis is strengthened by the mass balances carried out and summarized in Table 3. The conservative or non-reactive materials such as sulphate, calcium and ammonia all show good loading convergence based on water volume calculations. They show an excess in the Gerald Lake basin of from 4 to 24% which is very acceptable from an analytical standpoint considering the uncertainties involved. From an analytical standpoint, this means that virtually all of the material released from water Reservoir No. 2 is still in Gerald Lake. Based upon the mass balance data shown in Table 3, a maximum of 4% of the ammonia, 2% of the sulphate and less than 1% of the other parameters analyzed for could have entered the muskeg drainage channel. With the exception of ammonia and sulphate, these values are indistinguishable from background.

Expressed another way, all of the data independently point to the fact that in excess of 98% of the water released from Reservoir No. 2 was still in Gerald Lake during 15-17 January when the profiled water and sediment analyses were carried out upon which these analyses are based. Within Gerald Lake itself, the analyses suggest that over 90% of all of the material lost from Reservoir No. 2 is in the sediments or deep waters of Gerald Lake below a two metre depth. Conductivity and temperature profiles conducted in mid-February suggest that some slow mixing of surface and deeper water is occurring under the ice. This mixing should be complete within a couple of weeks after ice-out when wind induced and thermal turnover occur.

5.0 ENVIRONMENTAL SIGNIFICANCE

The spill from Reservoir No. 2 may be expected to have caused disturbance to the receiving environment through three major mechanisms. The first is physical, the second is chemical and the third radiological. The environmental significance of allowing unrestricted downstream discharge of water from Gerald Lake at spring breakup is also discussed.

5.1 Physical Impacts

The most significant effect of the spill from an environmental standpoint is related to the blanketing of the littoral zone in the northwest corner of Gerald Lake by sands and silts washed in from the eroding dyke. Up to 10% of the littoral zone along the northern and eastern side of Gerald Lake may have been affected. Benthic invertebrate populations in this area would have been blanketed and a high mortality of the resident benthic invertebrate community in this area is expected to have occurred.

Beyond this area, the deposition of silts and clays within the deeper parts of the lake at thicknesses on the order of 1 cm or more may have caused some mortality. Although many of the burrowing species may have survived the initial blanketing, a further protracted mortality may result related to a reduction in available food supply due to burying by the silts and clays. Since the available data suggest the turbidity plume sunk upon entering Gerald Lake, the majority of the littoral or shoreline zone (surface to 2-3 m depth) would have been unaffected by the spill.

Burbot, the only large fish species reported from the lake, generally move to shallow littoral waters to spawn from January to March. It is not known where the sandy, gravelly littoral areas are that burbot spawn on in Gerald Lake, but it is likely they are along the southern and eastern shores. It is thus possible that up to 25% of burbot spawning areas could have been affected to some degree. This impact is likely to be of a short-term nature and within an estimated two to three years natural wave action will have cleaned the silts and clays out of the debris deposited in the littoral area in the north-eastern corner of Gerald Lake, and the remaining sands and gravel will make ideal burbot spawning habitat.

Over a period of several years, the silts and clays washed into the lake will mix into the organic sediments and the deeper lake sediments will have an invertebrate productivity due to improved habitat just as high if not higher than that which existed prior to the spill.

In summary, the wash in of sands, silts and clays from the eroding dyke are expected to have affected directly impacted invertebrate communities and possibly some portion of the lakes burbot population. This impact is expected to be measurable locally, but not on a lake-wide basis. The impact is expected to be relatively short-lived, on the order of a couple of years after which the lake ecosystem as a whole will return to close to pre-spill conditions, with any deviation expected to be toward a condition of higher productivity and greater diversity. No significant or measurable physical hydrologic impacts are expected due to the flooding of the muskeg channel to the north and west of Gerald Lake.

No significant or measurable impacts are expected to be observed related to the thermal input to Gerald Lake. Thermal input to the muskeg channel upstream of the temporary dyke was judged to have been insignificant as the data indicate surface water from Gerald Lake at close to $0^{\circ}C$ flowed into the muskeg channel.

5.2 Chemical Impacts

The chemical materials released to Gerald Lake can be discussed in terms of broad categories. These are general water quality parameters such as pH, and conductivity; major anions and cations such as calcium, magnesium, sulphate and chloride; nutrients such as phosphate, nitrate and ammonia; and trace elements such as arsenic, nickel, lead and zinc. Table 4 shows the concentrations in the deep part of Gerald Lake, the concentrations in the shallow part of Gerald Lake and the muskeg area, the level at which toxic or harmful effects may be expected and the desirable level for balanced ecosystem functioning and water supply use. The only chemical material which may have had an impact would have been the ammonia, pH combination in the deep waters of Gerald Lake. Concentrations found there were on the borderline of toxic and may have resulted in the death of some bottom-dwelling invertebrates. Fish species can generally sense harmful levels of chemicals such as unionized ammonia and swim with the concentration gradient to cleaner water. If any burbot were still inhabiting the deep

TABLE 4: COMPARISON OF WATER QUALITY IN GERALD LAKE IN MID-JANUARY WITH HARMFUL* AND DESIRABLE LEVELS

Parameter	Gerald Lake		Significance	
	Deep Basin	Shallow Water and Muskeg Channel	Harmful or Toxic Levels	Desirable Level
pH	9.0	7.0		6.5-8.5
Conductivity	350	50		
Calcium (mg/L)	67	4.5		1,000
Sulphate (mg/L)	160	10		5,000
Magnesium** (mg/L)	3	0.5		1,500
Chloride** (mg/L)	5	2		1,500
Nitrate** (mg/L)	0.05	0.01		10
Ammonia Total (mg/L)	5	0.3		0.5
Unionized	0.5	0.0004	0.2	0.02
Arsenic (ug/L)	15	5	1,000	200
Nickel (ug/L)	50	15	100	50
Lead (ug/L)	3	3	500	100
Zinc (ug/L)	5	5	500	100
Uranium (ug/L)	70	10		20
Radium-226 (Bq/L)	0.5	0.05		0.1

*Those levels at which no toxic effects on aquatic biota would be expected.

**Estimated Concentrations

waters of Gerald Lake, it is expected they would have moved into shallower water where ammonia levels were non-toxic. If, for some reason, any fish stayed in the deep water, the unionized ammonia may kill them over a period of a week or so. In the absence of continued input, the toxic effects of ammonia are short-lived. Ammonia supplies an energy source for nitrifying bacteria which convert it to nitrites and nitrates. These materials are, in turn, converted to nitrogen gas by denitrifying bacteria or taken up as nutrients by algae and other aquatic plants. Further analyses are thus predicted to show decreasing ammonia levels.

The adsorption of trace elements and radionuclides to sediments will result in a buildup of these materials in the deep basin sediments of Gerald Lake. The mass balance calculations show that the levels monitored in mid-January are close to the maximum levels that could be expected. Figure 4 shows the actual monitored levels and the regional sediment range for lakes of this type. The past spill levels are within the normal background range for lakes in northern Saskatchewan. The effect of these levels on the aquatic population is assessed as being insignificant.

5.3 Radiological Impacts

The chemical toxicity of uranium is approximately equal to its radiotoxicity. If the no effect level observed in both human and animal studies is used and a ten-fold safety factor is applied and continuous consumption of two litres of water a day assumed, the "safe level" for drinking water would be 60 ug/L of total uranium. If both U-238 and U-234 isotopes were assumed to be present in secular equilibrium, this would be an activity of 1.5 Bq/L. The Canadian drinking water standard of 20 ug/L uses animal data for its rationale. It assumes only half of the daily intake comes from uranium in drinking water, and applies a 100-fold safety factor. The fully mixed uranium concentration in Gerald Lake after spring breakup is estimated to be less than 50 ug/L.

Radiological risk can best be expressed in terms of delayed fatalities. UNSCEAR 1982 has published risk factors which state that, for a radiation dose of 60-man sieverts, one delayed fatality will result. If a person were to use as their drinking water, water from Gerald Lake for a year, they would receive a radiation dose of (1.2 Bq/L (50 ug/L) x 730 L/year = 876 Bq consumption x 8×10^{-8} Sv/Bq consumed = 7×10^{-5} man sieverts or) 70×10^{-6} man sieverts. Since one delayed fatality can be expected to occur for every 60 man

sieverts, this means that the risk of premature death from drinking the water in Gerald Lake due to its uranium content at 2 L/day for one year would be roughly one in one million. The comparative radiological risk for consuming the radium in Gerald Lake after mixing in the spring, for a period of one year would be on the order of one in one hundred thousand.

The radiological effect on the aquatic biota of Gerald Lake is very low. Research data has shown that some radiation effects can be shown to occur in laboratory populations of aquatic animals at chronic doses on the order of one rad/hour. The dose rate received by benthic invertebrates burrowing into sediments in the middle of Gerald Lake where the highest concentrations of uranium and radium are found would be on the order of one mrads/hour or about one thousand times lower than the level at which any effects would be expected to be detectable in a laboratory population.

Thus, the radiological effect of the spill from Reservoir No. 2 on the aquatic population in Gerald Lake is judged to be insignificant. The potential radiological effect on anyone likely to consume Gerald Lake water directly or Gerald Lake water after it flows out of Gerald Lake and downstream is judged to be within those limits of risk normally accepted by society.

5.4 Effect of Unrestricted Discharge from Gerald Lake on Downstream Water Quality

The area of the Gerald Lake catchment basin is estimated to be on the order of twice the size of the lake or close to 20 ha. Average runoff yields for the region are near 6 L/sec/km^2. This would mean that the average annual flow out of Gerald Lake through the muskeg to Wolf Lake and Fox Lake, and eventually out of Yak Creek, would be on the order of 1.2 L/sec. The area of the Yak Creek catchment is estimated at 7.3 km^2 which would result in a mean annual flow of close to 44 L/sec.

If the concentrations in the water column of Gerald Lake, measured in mid-January, were to remain until spring breakup and fully mix in the lake before flowing out, the maximum outflow fluxes would be on the order of that shown in Table 5 for those parameters which had concentrations significantly different from background.

TABLE 5: INFLUENCE OF UNRESTRICTED DISCHARGE FROM GERALD LAKE ON DOWNSTREAM WATER QUALITY

Parameter	Max. Avg. Annual Flux from Gerald Lake	Projected Annual Avg. Flux from Yak Creek	Percent Incremental Concentration at Mouth of Yak Creek	Absolute Concentrations in David Creek
Uranium	57 ug/sec	4 mg/sec	1.4%	0.5 ug/L
Ammonia	2.6 mg/sec	$5x10^2$ mg/sec	0.5%	10 mg/L
Calcium	38 mg/sec	$4x10^4$ mg/sec	0.01%	70 mg/L
Sulphate	96 mg/sec	$1.2x10^5$ mg/sec	0.01%	175 mg/L
Radium	0.3 Bq/sec	6 Bq/sec	5%	0.02 Bq/L

Once these materials mixed in Wolf and Fox Lakes, they would add incrementally to the concentrations in those lakes by the percentages shown in Table 5. A further mixing in David Creek would drop these percentages another seven- to ten-fold. Levels of materials that would enter Yak Creek from Gerald Lake at spring breakup are predicted to be analytically undetectable and at levels where the incremental environmental effect would be completely insignificant.

6.0 CONCLUSIONS

1. Of the water that spilled from water storage Reservoir No. 2 on 5 January 1984, all of the available evidence suggests that over 90% of the water spilled entered the deep basin of Gerald Lake.

2. The surface waters of Gerald Lake contain less than 10% of the water lost from Reservoir No. 2 and the water displaced from Gerald Lake into the muskeg channel contains less than 2% of the water released from Reservoir No. 2.

3. Of the trace contaminants released from Reservoir No. 2, more than 80% of the nickel, arsenic and radium-226 had entered the deep Gerald Lake sediments by mid-January. Less than 15% of these materials remained in solution or suspension in the deep waters of Gerald Lake and less than 5% in the surface waters of Gerald Lake. The quantity of trace contaminants that entered the muskeg drainage channel was too small to be accurately determined, being much less than 1% of the total release.

4. Uranium has a relatively high solubility in the oxidized state and environmental monitoring showed that, of the uranium lost from water storage Reservoir No. 2, about 50% was accounted for in mid-January in the deep sediments of Gerald Lake, 45% had stayed in solution or suspension in the deep waters of Gerald Lake, and 5% was found in the surface waters of Gerald Lake. A quantity too small to separate from background levels (less than 0.3%) may have moved into the muskeg channel and area upstream of the temporary dyke.

5. Of the soluble materials released, such as calcium, sulphate and ammonia, approximately 93% was present in the deep waters of Gerald Lake, 5% was present in the surface waters of Gerald Lake, and about 2% could be accounted for in the muskeg drainage channel in mid-January. Data collected in mid-February suggests that the same general condition will exist until mixing occurs just after ice-out in Gerald Lake.

6. Based upon the above, all of the environmental-related impacts are confined to the Gerald Lake basin. These impacts related to:

- sediment effects associated with the deposition of an estimated 1,000 m^3 of sands, silts and clays in Gerald Lake;

- hydraulic effects of the scouring effect of water flowing into the northeast corner of Gerald Lake; and

- possible toxic effects of the particular pH and ammonia combination found in the deep waters of Gerald Lake.

All of these impacts are of reltively short duration and none would be judged significant within the overall environmental setting of the Gerald Lake basin.

7. Levels of radium-226, uranium and trace metals found outside of the deep waters and sediments of Gerald Lake are very close to background, and the levels found do not exceed Federal drinking water standards.

8. Of the levels of materials released from water supply Reservoir No. 2 found in the deep waters of Gerald Lake, only uranium exceeds Federal drinking water standards. Levels of radium-226 exceed Provincial surface water quality objectives because of their much more restrictive nature. It should be recognized, however, that in order for an individual to consume enough radium-226 to exceed the maximum allowable dose limit, this individual would have to drink $3x10^4$ litres or 6,600 gallons a year from the deep waters of Gerald Lake.

9. Upon mixing of the waters of Gerald Lake following spring breakup, it is possible that natural in lake sedimentation processes will have reduced levels of uranium and radium to the point where all the waters in the Gerald Lake system meet Federal drinking water standards.

10. No significant radiological impacts appear to have occurred to the natural environment as a result of the spill of water from Reservoir No. 2 and none are expected to occur in the future.

11. If the water from Gerald Lake is allowed to drain through its natural course down through Wolf Lake, no adverse nor significant downstream impacts are anticipated.

12. If the water from the deep basin of Gerald Lake was to be pumped out and put through the water treatment system in the mill before discharge to Wolf Lake, it would result in no significant improvement in downstream water quality.

7.0 RECOMMENDATIONS

1. Because natural sedimentation processes can be expected to continue to remove trace elements and radionuclides from the water column and deposit them in the sediments of Gerald Lake, it is recommended that monthly monitoring of surface, mid-depth and bottom waters be carried out at three stations over the main basin of Gerald Lake until spring breakup.

2. If the water quality monitoring recommended confirms that the quality of water flowing out of Gerald Lake and through the muskeg area to Wolf Lake at spring breakup will not significantly affect the water quality in Wolf Lake, it is recommended that, at breakup, runoff water from the Gerald Lake basin be allowed to follow its natural course into Wolf Lake.

3. Because suspended particulates in water play a very important role in the removal of trace elements from the water column and into the sediments, it is recommended that water quality monitoring of the waters in Gerald Lake be carried out on the soluble portion as defined by its ability to pass through a 0.45 micron filter.

4. Because the ammonia in Gerald Lake is expected to nitrify to nitrite and nitrate, it is recommended that nitrites and nitrates also be analyzed for in any continuing monitoring program until ammonia levels return to background.

5. Any future sediment monitoring studies should be carried out using a coring device in order that freshly deposited spill-related sediments can be analytically separated from original lake sediments.

6. If it is decided to remove water from Gerald Lake, it is recommended that the intake for any pumping system be placed at about a 7-8 metre depth in the 10-metre deep basin so that the deep waters are the first removed and that this be carried out prior to breakup and the natural mixing of the waters of Gerald Lake.

POOR

QUALITY

ORIGINAL